Year: 2020

Clinical Study of the Influence of Ambient Light Scanning Conditions on the Accuracy (Trueness and Precision) of an Intraoral Scanner

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Abstract: PURPOSE To quantify the impact of ambient lighting conditions on the accuracy (trueness and precision) of an intraoral scanner (IOS) when maxillary complete-arch and maxillary right quadrant digital scans were performed in a patient. MATERIAL AND METHODS One complete dentate patient was selected. A complete maxillary arch vinyl polysiloxane impression was obtained and poured using Type IV dental stone. The working cast was digitized using a laboratory scanner (E4 Dental Scanner; 3Shape) and the reference standard tessellation language (STL file) was obtained. Two groups were created based on the extension of the maxillary digital scans performed namely complete-arch (CA group) and right quadrant (RQ) groups. The CA and RQ digital scans of the patient were performed using an IOS (TRIOS 3; 3Shape) with 4 lighting conditions chair light (CL), 10 000 lux, room light (RL), 1003 lux, natural light (NL), 500 lux, and no light (ZL), 0 lux. Ten digital scans per group at each ambient light settings (CL, RL, NL, and ZL) were consecutively obtained (n = 10). The STL_R file was used to analyze the discrepancy between the digitized working cast and digital scans using MeshLab software. Kruskal-Wallis, one-way ANOVA, and pair-wise comparison were used to analyze the data. RESULTS Significant difference in the trueness and precision values were found across different lighting conditions where RL condition obtained the lowest absolute error compared with the other lighting conditions tested followed by CL, NL, and ZL. On the CA group, RL condition also obtained the best accuracy values, CL and NL conditions performed closely and under ZL condition the mean error presented the highest values. On the RQ group, CL condition presented the lowest absolute error when compared with the other lighting conditions evaluated. A pair-wise multicomparison showed no significant difference between NL and ZL conditions. In all groups, the standard deviation was higher than the mean errors from the control mesh, indicating that the relative precision was low. CONCLUSIONS Light conditions significantly influenced on the scanning accuracy of the IOS evaluated. RL condition obtained the lowest absolute error value of the digital scans performed. The extension of the digital scan was a scanning accuracy influencing factor. The higher the extension of the digital scan performed, the lower the accuracy values obtained. Furthermore, ambient light scanning conditions influenced differently depending on the extension of the digital scans made.

DOI: https://doi.org/10.1111/jopr.13135

Revilla-León, Marta; Subramanian, Sai Ganesh; Özcan, Mutlu; Krishnamurthy, Vinayak Raman (2020). Clinical Study of the Influence of Ambient Light Scanning Conditions on the Accuracy (Trueness and Precision) of an Intraoral Scanner. Journal of Prosthodontics, 29(2):107-113.
DOI: https://doi.org/10.1111/jopr.13135

Clinical study of the influence of ambient light scanning conditions on the accuracy (trueness and precision) of an intraoral scanner

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Conflict of Interest

The authors did not have any conflict interest, financial or personal, in any of the materials described in this study.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

Keywords

Accuracy; CAD-CAM; Intraoral digitizers; Intraoral scanners; Influencing factors.

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ABSTRACT

Purpose. To quantify the impact of ambient lighting conditions on the accuracy (trueness and precision) of an intraoral scanner (IOS) when maxillary complete-arch and maxillary right quadrant digital scans were performed in a patient.

Material and Methods. One complete dentate patient was selected. A complete maxillary arch vinyl polysiloxane impression was obtained and poured using Type IV dental stone. The working cast was digitized using a laboratory scanner (E4 Dental Scanner; 3Shape) and the reference standard tessellation language (STL file) was obtained. Two groups were created based on the extension of the maxillary digital scans performed namely complete-arch (CA group) and right quadrant (RQ) groups. The CA and RQ digital scans of the patient were performed using an IOS (TRIOS 3; 3Shape) with 4 lighting conditions chair light (CL), 10 000 lux, room light (RL), 1003 lux, natural light (NL), 500 lux, and no light (ZL), 0 lux. Ten digital scans per group at each ambient light settings (CL, RL, NL, and ZL) were consecutively obtained (n=10). The STL_R file was used to analyze the discrepancy between the digitized working cast and digital scans using MeshLab software. Kruskal-Wallis, 1-way ANOVA, and pair-wise comparison were used to analyze the data.

Results. Significant difference in the trueness and precision values were found across different lighting conditions where RL condition obtained the lowest absolute error compared with the other lighting conditions tested followed by CL, NL and ZL. On the CA group, RL condition also obtained the best accuracy values, CL and NL conditions performed closely and under ZL condition the mean error presented the highest values. On the RQ group, CL condition presented the lowest absolute error when compared with the other lighting conditions evaluated. A pair-wise multi-comparison showed no significant difference between NL and ZL conditions. In all

groups, the standard deviation was higher than the mean errors from the control mesh, indicating that the relative precision was low.

Conclusions. Light conditions significantly influenced on the scanning accuracy of the IOS evaluated. RL condition obtained the lowest absolute error value of the digital scans performed. The extension of the digital scan was a scanning accuracy influencing factor. The higher the extension of the digital scan performed, the lower the accuracy values obtained. Furthermore, ambient light scanning conditions influence differently depending on the extension of the digital scans made.

Intraoral scanner (IOS) devices provide a clinically acceptable alternative to conventional impression making for tooth and implant-supported crowns and short-span fixed dental prostheses.[1-13] Different factors influence scanning accuracy including technology of the IOS selected,[1,10-23] calibration,[23] handling and learning,[24,25] scanning conditions,[26,27] surface characteristics,[28-31] scanning protocols,[13,21,30,31] and the post-processing methods performed.

Recently, in vitro studies have demonstrated the impact on the ambient scanning lighting conditions on the scanning accuracy of different IOSs.[32-34] Based on those reports, a scanning accuracy difference can be expected between 37% to 44% among the different lighting conditions evaluated.[33] Moreover, the lighting condition should be selected based on the IOS used. However, its impact on scanning accuracy when performed in vivo remains unclear.

Trueness and precision define the scanning accuracy of an IOS (ISO 5725-1 and DIN 55350-13).[35-37] Trueness relates to the capability of the scanner to replicate a dental arch as close to its true form as possible without deformation or distortion, while precision specifies the degree of identical images acquired by repeated scanning under the same conditions.[35-37]

The purpose of the present study was to quantify the impact of different ambient lighting conditions on the accuracy of an IOS system when performing digital scans on a patient. The null hypotheses were that no significant difference would be found in the digital scan accuracy (trueness and precision) of the IOS tested under the 4 different ambient scanning light conditions evaluated, and that no significant difference would be found in the maxillary complete-arch or maxillary right quadrant digital scans accuracy (trueness and precision) under the 4 ambient lighting conditions tested.

Materials and methods

A complete dentate patient was selected in a private practice in Spain. Extraoral, intraoral, and radiographic evaluations revealed acceptable oral health. The maxillary teeth did not present any dental restoration. A complete maxillary arch impression was obtained using a vinyl polysiloxane dental material (Virtual heavy and light viscosity regular set; Ivoclar Vivadent). The impression was poured with Type IV dental stone (GC Fujirock EP; GC) after mixing 22 ml water with 100 g dental stone under vacuum for 30 seconds. The working cast was recovered after the dental stone had completely set.

The working cast was digitized as the reference model using a structured light laboratory scanner (E4 Dental Scanner; 3Shape) at a constant room temperature (23ºC) following the manufacturer´s recommendations. A standard tessellation language file (STL_R file) was obtained. The laboratory scanner had been previously calibrated following the manufacturer's instructions. The manufacturer reports for this scanner an accuracy of 4 μm.

A experienced prosthodontist (M.R.L.) performed digital scans in the patient using an IOS (TRIOS 3; 3Shape) at 4 ambient light settings (Table 1). The lighting conditions selected followed the European Standard for Illumination (EN 12464) recommendations for a private practice illumination.[38,39] The manufacturer´s scanning protocol was followed (Fig 1) and the IOS was both 3D and color calibrated following the manufacture´s recommendations every time that the ambient lighting condition was changed.

For the CL group, a room with a dental chair (A-dec 500; Adec) and no windows was chosen. The LED light of the chair had an intensity of 15000 lux and 4100 K which was oriented 45 degrees at a distance of 58 cm to the patient’s mouth. The lighting in the room was 6 fluorescent tubes of 54 W, 5000 lumens (GE F54W-T5-841-ECO; Ecolux High Output) with a white spectrum color temperature (4100 ºK) ceiling light, and 10000 lux measured with a light meter (LX1330B Light Meter; Dr. Meter Digital Illuminance).

For the RL group, the light of the chair was turned off and only the ceiling light was used, with no windows or natural light. The illuminance of the room was 1003 lux which was measured with the same light meter. For the NL group, a room with natural light of 500 lux measured with the same light meter obtained through windows. For the ZL group, a room with no light and no windows was used.

At each light condition, 10 maxillary complete-arch digital scans were performed consecutively on the patient after placing a lip retractor (OptraGate; Ivoclar Vivadent) and drying the scan area to achieve relative isolation. Subsequently, each digital scan was performed and the mobile tissue areas were trimmed from the scan using the IOS software to eliminate potential areas of error due to the mobility of the soft tissue (Fig 2). In order to standardize the procedure, the tissues located 3 mm apically to the gingival margins of the teeth were trimmed.

The control STL_R file was used as a reference digital model to compare the distortion with the 40 STL files obtained. In the experiment, trueness was defined in terms of the average distance between the reference and scanned model. The lower the distance, the higher the trueness. Based on this, precision was defined in terms of the standard deviation of the average absolute distances measured between all scanned samples and the reference model.[35-37] A 3D mesh processing open-source software (MeshLab; MeshLab) was used for 3D mesh processing as it provides simplified processing of large unstructured meshes and tools for editing, cleaning, and inspecting meshes. Specifically, the software selected was used for pre-processing the scanned models of the teeth. MATLAB was used for performing statistical analysis on data gathered.

The STL file format represents the scanned data as a surface made of small triangles (or *triangle soup)*, or in other words, a set of topologically non-connected triangles $\Delta_i = \{\boldsymbol{p}_{i1}, \boldsymbol{p}_{i2}, \boldsymbol{p}_{i3}\}, i \in [1, n]$, that define the surface of the digitized teeth. Here, $\boldsymbol{p}_{ij} \in \mathbb{R}^3$ is the j^{th} vertex of the i^{th} triangle ($j \in \{1,2,3\}$). This implies that each vertex on the mesh appears more than once in the triangle soup. Each scanning process results in a completely different set of triangles, all representing the same physical model. For this, the co-incident vertices of the triangle soup were unified to construct a topologically connected triangle mesh$M(V, F)$. The vertex unification was performed when the geometry was imported in MeshLab. Here, $V = \{\boldsymbol{v_1}, \dots, \boldsymbol{v_n}\}, \boldsymbol{v_i} \in \mathbb{R}^3$ was the set of unified vertices and $F = \{(i, j, k)\}, i, j, k \in [1, n], i \neq j \neq k$ described the triangular faces formed by the vertices (Fig 3A).

In order to perform statistical analysis of the scanned data, the primary task was to compute the spatial deviations of a treatment scanned model $S(V_S, F_S)$ with respect to the control STL model $T(V_T, F_T)$. For a vertex $\boldsymbol{v} \in V_S$, the deviation was simply defined as the distance, $d_T(\boldsymbol{v})$, between $\boldsymbol{v}$ and the closest face $\boldsymbol{f} \in F_T$ to $\boldsymbol{v}$.[37] Mathematically, this could be computed as the absolute value of the dot product $\langle \boldsymbol{v} - \boldsymbol{c_f}, \boldsymbol{n_f} \rangle$. Here, $\boldsymbol{c_f}$ and $\boldsymbol{n_f}$ were the centroid and normal of the closest face $\boldsymbol{f}$ respectively (Fig 3B). Given a scan S, the error metric was then defined as the set $E(S) = \{d_T(\boldsymbol{v})\ \forall\ \boldsymbol{v} \in V_S\}$ (Fig 4).

The trueness value of a given lighting condition was calculated by the mean of the absolute error values for each of the meshes scanned in that group. The precision of the lighting group represented the consistency of the values obtained from the digital scans. For precision calculation, the standard deviation of each of the mesh files in a given lighting group was used for comparison.

Each of the STL files were imported into MeshLab along with the control file. In order to evaluate the error metric for the in-vivo digital scans, the following 2 conditions were ensured.

Firstly, both the maxillary complete-arch scanned mesh and the control mesh were orientable or had two well-defined sides. This meant that the meshes had consistent surface normal vector at every point. This condition was obtained by unifying the vertices when every mesh was imported in MeshLab. And secondly, both mesh files were properly aligned.

The alignment of the meshes was performed using the iterative closest point algorithm[40] using the MeshLab software. Firstly, the maxillary complete-arch scanned and the reference mesh files were loaded into MeshLab software (Fig 5A). Four prominent landmarks were chosen (Fig 5B) in the contour of the two meshes and mapped to each other. These landmarks were chosen since they were easily identifiable, distinct, and had a specific feature. Also, these landmarks were made common across all the scans. A similar work studying the precision of intraoral scanning have roughly aligned the meshes manually.[2] Once the correspondence was completed, the iterative closest point algorithm was applied until the error between the aligned meshes converged to a minimal value (Fig 5C). The error value after convergence was observed to be lesser than 0.04 mm for all the scans.

The signed distance metric was computed between the maxillary complete-arch scanned mesh and the reference mesh and the distance was stored as a vertex quality in a PLY file. This file was read in MATLAB for carrying out statistical evaluation.

The extreme outliers were removed before performing the statistical analysis (Fig 6). These outliers occurred due to some data points that lied in the boundary of the scanned mesh and were not aligned to the reference mesh. This caused the signed distance error metric to surge at these regions, thus this portion of the mesh - that had this particular defect below an assumed height from the mesh - was considered to be trimmed. However, this procedure may remove other important data points since the mesh geometry was highly detailed. This problem was addressed by identifying and removing the values that lied more than 3.0 times the interquartile range below the first quartile or above the third quartile. In this way, the aberrations were removed prior to doing the statistical tests. A priori power analysis was conducted across different groups using G* power (v3.1.9.4). The alpha value was assumed to be 0.05 (power = 0.99, actual power = 0.99) and appropriate effective size was calculated using the mean and standard deviation of the groups. The required sample size was found to be considerably lesser than the sample size of data collected. This is due to the high sampling size of the vertex data collected from the scanner. Thus, there was sufficient statistical power.

The normality of the distribution of data was investigated using Shapiro-Wilk test. Since most of the samples were non-normal, groups were compared using Kruskal-Wallis 1-way ANOVA Test. The significance level was assumed to be $p<.05$.

Results

The trueness and precision of digital scans values obtained per lighting condition are presented in Table 2 and 3. In all groups, the standard deviation was higher than the mean errors from the control mesh.

The trueness and precision of the digital scans performed at 4 different ambient scanning light conditions was analyzed. Significant different trueness and precision values were found (Table 4). In terms of trueness, RL condition obtained the lowest absolute error compared with the other lighting conditions tested followed by CL, NL and ZL (Fig 7).

In the CA group, significant different trueness and precision values were found (Table 5). In terms of trueness, the digital scans were found to have least absolute error in RL condition. The CL and NL conditions performed closely and under ZL condition the mean error presented the highest values (Figs 8 and 9). On the QA group, significant different trueness and precision values were found (Table 6). In terms of trueness, CL condition presented the lowest absolute error when compared with the other lighting conditions evaluated. Pair-wise multi-comparison showed no significant difference between NL and ZL conditions (*P*=.910).

Discussion

Significant differences were found among the four lighting conditions using the IOS system evaluated, and significant differences were found among the different ambient lighting conditions for both the maxillary complete-arch and right quadrants groups; consequently, the three null hypotheses were rejected.

The lighting conditions selected in the present study were based on the scarce recommendations for the optimal operating light in a dental operatory,[38,39,41] specifically on the European Standard for Illumination (EN 12464) that recommends 500 lux for general illumination, 1000 lux at the medical or examination rooms and 10000 lux for the operating cavity.[38] In the present study, the chair, room, and natural light illumination replicated the recommended European Standards.

A previous study evaluated the influence on the ambient light scanning conditions on the accuracy of different IOSs.[33] In that in vitro study, a maxillary typodont and a mannequin was used to perform complete-arch digital scans at 4 different ambient light scanning conditions which were exactly the same ones tested on the present clinical study. When evaluating the Trios 3 IOS system, the authors reported a mean trueness value 105.59 µm for the RL condition, 118.12 µm for ZL, 132.69 µm for CL, and 139.49 µm for NL. Based on the results of the present study, when analyzing the influence of different light conditions on the different digital scans performed with the Trios 3 IOS, RL conditions obtained the lowest absolute error values (mean 76.33 µm, median 51.44 µm). However, differences could be explained due to different conditions at which the present project was developed such as a real patient and natural dentition scanned. Furthermore, in the in vitro study, the control STL file was obtained by scanning the typodont directly using a laboratory dental scanner, but in the present study the control STL file was obtained by scanning the working cast that was fabricated from a dental impression. The discrepancy between the working cast and the control STL file might be higher than the typodont and the control STL file, which may decrease or increase the real scanning accuracy values obtained.

The results obtained demonstrated that the extension of the digital scan influenced scanning accuracy where the CA group obtained significantly higher absolute error mean values compared with the RQ group. This result is in agreement with previous studies.[42] Furthermore, in both CA and RQ groups, significant difference was found among the different light conditions tested; but, while RL condition obtained better accuracy results in the CA group, CL condition presented with better accuracy outcomes in the RQ group. This could be explained by the difference space at which the light is distributed on the different CA and RQ digital scans.

The present study showed that the standard deviation was higher than the mean errors from the control mesh, indicating that the relative precision was low. Previous studies that have analyzed the accuracy of the digital scans performed with different IOSs systems,[1-7,9-31,42] have not provided analysis on how lighting conditions affect scanning accuracy which make questionable the accuracy values reported.

The results of the present study demonstrated the importance of the light scanning conditions standardization while performing a digital scan. Based on the data obtained in the present study, the accuracy on the IOS tested decreased between 7% to 43% by selecting a different lighting condition. Clinicians should understand the ambient lighting condition as a critical influencing factor on the scanning accuracy of IOSs, and a light meter should be included into the armamentarium of the digital device. Additional studies are recommended to fully understand the impact of lighting conditions on the accuracy of the available intraoral digitizer systems.

Conclusions

Ambient lighting conditions significantly influenced on the scanning accuracy of the IOS system evaluated, where RL condition (1000 lux) obtained the lowest absolute error value of the digital scans performed. Furthermore, the extension of the digital scan was a scanning accuracy influencing factor; the higher the extension of the digital scan performed, the lower the accuracy values obtained. Additionally, ambient lighting conditions influence differently depending on the extension of the digital scans made. RL condition obtained the lowest absolute error values when complete-arch digital scans were performed, but CL condition presented the best accuracy values on the right quadrant digital scans obtained. Lastly, in all groups, the standard deviation was higher than the mean errors from the control mesh, indicating that the relative precision was low.

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TABLES

Table 1. Description of the various ambient light conditions evaluated.

LIGHT CONDITION	Chair light 10 000 lux 4100ºK	Room light 1003 lux 4100ºK	Windows 500 lux
CL*	Yes	Yes	No
RL**	No	Yes	No
NL***	No	No	Yes
ZL****	No	No	No

*CL: Chair light or 10000 lux; **RL: Room light or 1003 lux; ***NL: Natural light or 500 lux;

****ZL: No light or 0 lux

Table 2. Statistical aggregates of error for trueness and precision mean values for the different lighting conditions evaluated (CL, RL, NT, and ZL). All values are provided in microns (µm).

Lighting condition	Trueness		Precision
	Mean	Median	SD
CL	84.21	55.54	160.50
RL	76.33	51.44	193.92
NL	89.24	64.52	141.63
ZL	97.53	74.01	146.91

*CL: Chair light or 10000 lux; **RL: Room light or 1003 lux; ***NL: Natural light or 500 lux;

****ZL: No light or 0 lux

Table 3. Statistical aggregates of error for trueness and precision mean values for the CA and RQ groups for the different lighting conditions evaluated (CL, RL, NT, and ZL). All values are provided in microns (µm).

Group	Lighting condition	Trueness		Precision
		Mean	Median	SD
Complete arch (CA)	CL	114.91	77.33	166.91
	RL	73.22	43.95	199.42
	NL	109.92	77.52	136.94
	ZL	127.37	92.16	146.17
Right quadrant (RQ)	CL	60.78	28.78	131.15
	RL	96.94	47.89	181.17
	NL	85.31	44.87	147.49
	ZL	85.27	45.46	142.11

*CL: Chair light or 10000 lux; **RL: Room light or 1003 lux; ***NL: Natural light or 500 lux; ****ZL: No light or 0 lux

Table 4. P-value obtained from pair-wise multi-comparison using Kruskal Wallis test for the different lighting conditions tested.

Lighting condition	CL	RL	NL	ZL
CL	1	<.0001	<.0001	<.0001
RL	<.0001	1	<.0001	<.0001
NL	<.0001	<.0001	1	<.0001
ZL	<.0001	<.0001	<.0001	1

*CL: Chair light or 10000 lux; **RL: Room light or 1003 lux; ***NL: Natural light or 500 lux; ****ZL: No light or 0 lux

Table 5. For the maxillary complete-arch digital scans (CA group), the P-value obtained from pair-wise multi-comparison using Kruskal Wallis test for the different lighting conditions tested.

Lighting condition	CL	RL	NL	ZL
CL	1	<.0001	<.0001	<.0001
RL	<.0001	1	<.0001	<.0001
NL	<.0001	<.0001	1	<.0001
ZL	<.0001	<.0001	<.0001	1

*CL: Chair light or 10000 lux; **RL: Room light or 1003 lux; ***NL: Natural light or 500 lux; ****ZL: No light or 0 lux

Table 6. For the maxillary right quadrant digital scans (RQ group), the P-value obtained from pair-wise multi-comparison using Kruskal Wallis test for the different lighting conditions tested.

Lighting condition	CL	RL	NL	ZL
CL	1	<.0001	<.0001	<.0001
RL	<.0001	1	.021	.031
NL	<.0001	.021	1	.910
ZL	<.0001	.031	.910	1

*CL: Chair light or 10000 lux; **RL: Room light or 1003 lux; ***NL: Natural light or 500 lux; ****ZL: No light or 0 lux

FIGURES

Figure 1. A, Scanning protocol for the maxillary complete-arch digital scans performed followed the manufacturer´s recommendations. B, Scanning protocol for the maxillary right quadrant digital scans performed followed the manufacturer´s recommendations.

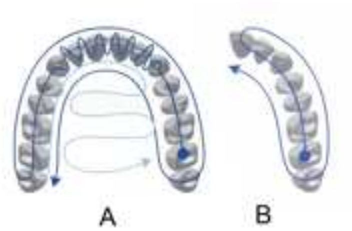

Figure 2. A, Maxillary right quadrant digital scan. B, Maxillary right quadrant digital scan with the mobile tissue areas trimmed using the IOS software.

Figure 3. Geometric preliminaries. A, Triangle soup (left) to triangle mesh (right) using vertex unification. B, Distance error metric.

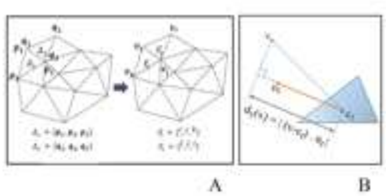

Figure 4. Color map of distance error metric for maxillary right quadrant digitized teeth mesh with reference mesh.

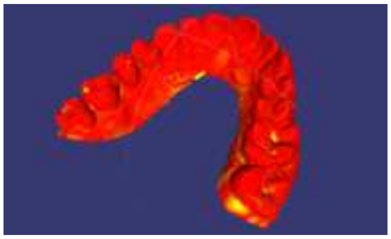

Figure 5. A, Misaligned meshes where the brown mesh is the control mesh and the blue mesh is one maxillary right quadrant scan. B, Point-based gluing of the two meshes. The feature inside the circle is the chosen landmark and the arrows shows the correspondence from the points in the maxillary right quadrant scan to the control mesh. C, Aligned meshes where the green mesh shows the aligned maxillary right quadrant scan using the point-based gluing and iterative algorithm.

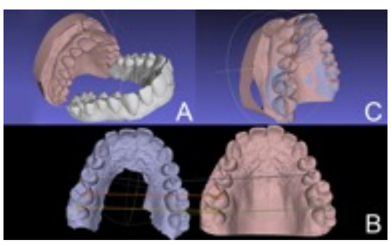

Figure 6. The points in the marked region were ignored for post-processing as it was identified as an outlier.

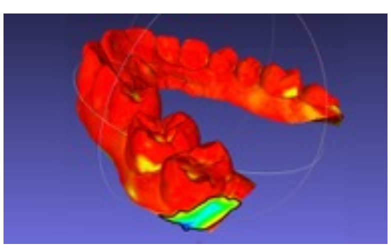

Figure 7. Boxplot for the digital scans performed with the minimum, maximum, interquartile range, medians, and outliers of measurements for the different lighting conditions tested.

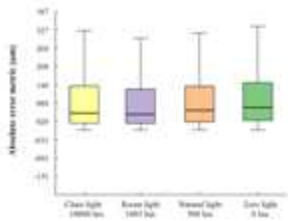

Figure 8. Boxplot for the maxillary complete-arch digital scans (CA group) with the minimum, maximum, interquartile range, medians, and outliers of measurements for the different lighting conditions tested.

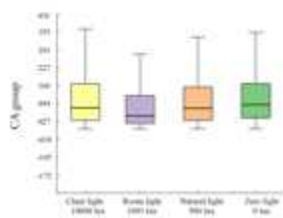

Figure 9. Boxplot for the maxillary right quadrant digital scans (RQ group) with the minimum, maximum, interquartile range, medians, and outliers of measurements for the different lighting conditions tested.